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SOME QUESTIONS OF THE DISCRETE CONTROL OF DEEP-WATER MANIPULATORS

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ABSTRACT. The use of manipulators to take geological samples and install measuring instruments on the ocean floor is discussed. Methods of performing complex operations using a manipulator connected by cable to the command element are presented.

The work involved in obtaining geological samples and in installing measuring instruments on the bottom in deep ocean waters requires the use of manipulators. Manipulators can be installed in special research submarines and bathyscaphes. In these cases, the operator sees the object in his immediate vicinity and the set of operations he performs can be quite complicated. /38

Attempts are presently being made to build an autonomous manipulator to do a predetermined volume of work in accordance with a special program. However, programmed control presumes, for the present, the performance of only the simplest operations, and proves to be unsuitable when the need arises to perform more complex, deep-water operations.

An unmanned vehicle with manipulators, lowered from the research vessel, can be used for investigations at depths of from 4 to 6 km. Control of the manipulators is by cable connecting them with the master element and control panel. Here the operator, who is aboard the research vessel can use deep-water television to observe the bottom on the television screen and use the manipulator to perform quite complex operations. The cable, in addition to its main purpose, which is the transmission of electrical control signals, also acts as the mechanical connection with the vehicle so, in addition to good electrical characteristics, must have high mechanical strength. The greater the depth of submersion of the vehicle, the more important the weight of the cable. The following formula can be used to approximate the maximum permissible length of the cable [1]

$$l_{\text{lim}} = \frac{F_t - (P_a - P_v)}{P - V},$$

where

F_t is the permissible cable tension;

P_a is the weight of the vehicle in air;

$P_a - P_v$ is the weight of the vehicle at the given depth;

P is the weight of one meter of cable;

v is the volume of one meter of cable.

Calculations show that the maximum permissible length of type TKPG-31 cable, which is a multicore cable, the strength element of which is steel braid, for example, is 1590 meters even when the vehicle has zero buoyancy and that of type TKPU-33 cable is 960 m [1].

Accordingly, a change must be made from multicore cables to rope-cable, /39 which has high mechanical strength, to control manipulators at great depths. An example of rope-cable for this purpose is the KTBF-6 logging cable with a break strength of 6 tons and the KTBF-8 with a break strength of 8 tons. These cables have three copper current-carrying conductors.

Manipulators with an open loop control system can be used when the work to be done with a manipulator is simple. Here the control system for manipulators with three current-carrying conductors in the cable can be successfully designed by using comparatively simple control system circuits. For example, let us assume communication channel multiplexing such that the working conductors in the cable can be used as desired by the operator to control one or the other of the manipulator drives. The simultaneous transmission of control signals to several drives is precluded in this case.

A manipulator must be controlled by a follow-up system when the type of work is rather complicated. This means that the simultaneous operation of several drives must be provided for. Delivery of a power supply to the vehicle from the surface for purposes of controlling two manipulators with seven degrees of freedom each calls for a cable with at least 16 current-carrying conductors. The simultaneous control of several manipulator drives working in the follow-up mode by a cable with three working conductors is possible only if the communication channel (CC) multiplexing system is more complicated than the open loop control system. Multiplexing can be code-, frequency-, and time-division.

Two CC multiplexing methods are used in practice: frequency-division, and time-division [2].

Each of n_0 transmitted signals is assigned its own carrier frequency for frequency-division channeling. Signals are separated by bandpass filters on the receiving side and, after passing through a demodulator, are fed into the amplifier input.

However, frequency-division channeling gets complicated and, consequently, is not very dependable, when a great many commands are transmitted. Then too, it is desirable to use the frequency-division channeling to transmit information with a broad frequency spectrum, and a maximum rational frequency of manipulator control signals not in excess of 1 Hz.

The requirements for simplicity, dependability, and small overall size of CC multiplexing force us to turn to the time-division channeling. Here commands are fed into the CC in a strictly determined sequence over a predetermined time interval. Switches are required to switch the cable at the command and reception points in turn to the corresponding command element potentiometers and control units. Dependable circuit operation requires that the distributors operate synchronously and in phase. Figure 1 is a block diagram of a discrete (pulsed) system such as this.

The circuit contains command element (CP) and feedback (FBP) potentiometer pickups. The error signal, ΔU, is picked off the CP and FBP cursors, fed into the amplifier, A, and then into the servo unit, SU, causing the working element, WE, to move according to this signal.

Time-division channeling thus results in the control signal being fed to the follow-up system discretely in the form of individual pulses, the amplitudes of which are equal to the input signal amplitude, and the duty ratio is determined by the number of commands transmitted over the CC. Figure 2 shows the time distribution of commands in the CC from n command element potentiometers.

The switch in Figure 1 henceforth will be called the pulse element (PE) of the automatic regulating system (ARS). /40

The output function of the PE is a sequence of pulses of width t_c and interval T, the envelope of which corresponds to continuous signal x(t) at the

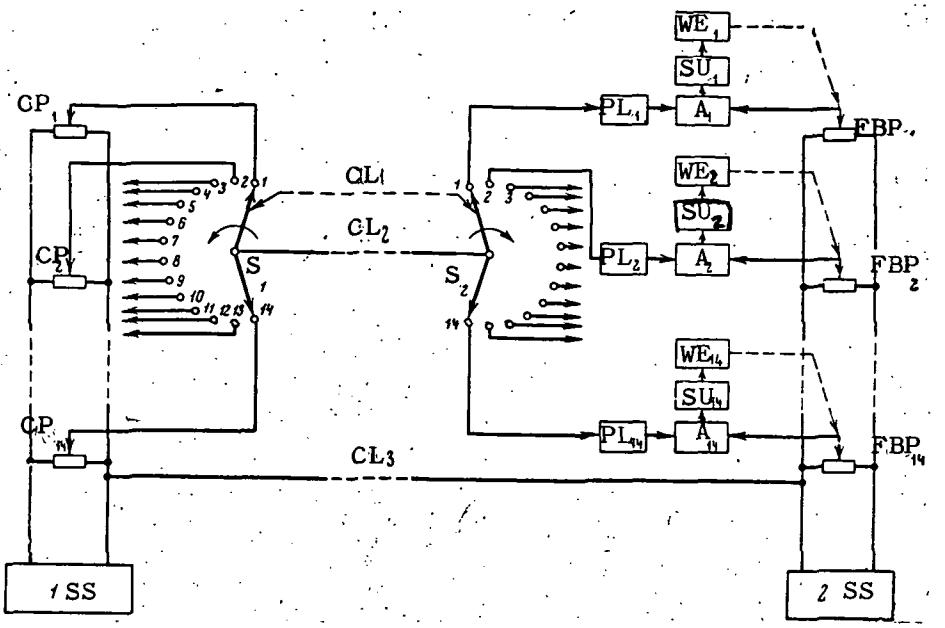

Figure 1. Block diagram of a manipulator control system using a time system for multiplexing a communication channel. 1 - 1st supply source; 2 - 2nd supply source.

PE input. The PE threfore can be considered to be an amplitude modulator with a carrier in the form of a sequence of single pulses [3]. The output function of the PE thus can be written as the product of the input function X(t), times the function of unit pulses $U(t_c, t)$ of width t_c and repetition interval T

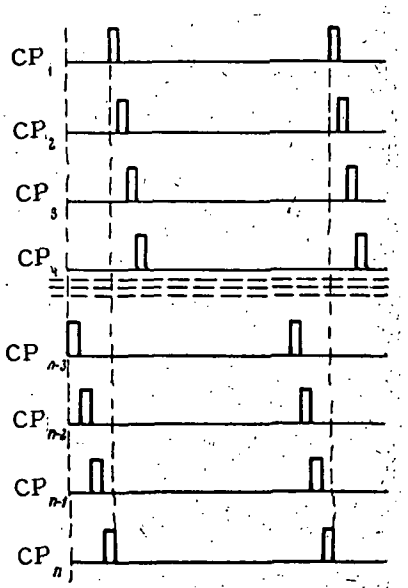

Figure 2. Time distribution of commands in the CC from n command element potentiometers.

$$A(t) = U(t_c, t) \cdot x(t). \qquad (1)$$

The function $U(t_c, t)$ is even and periodic, so it can be presented in the form of a Fourier series

(2)

where

$\omega_s = 2\pi/T$ is the chopping frequency

$$C_n = \frac{1}{T}\int_0^{t_c} e^{-jn\omega_s t}\,dt = \frac{1 - e^{-jn\omega_s t_c}}{jn\omega_s T};$$

C_n is the Fourier coefficients.

Substitution of C_n values into Eq. (2) yields the analytical notation for the function $U(t_c, t)$ 41

(3)

Eq. (3) makes it apparent that the function of unit pulses, apart from the constant component, contains an infinite set of harmonics, each of which is characterized by amplitude U_{ch}, angular frequency ω_{ch}, and initial phase ψ_{ch}

$$U_{ch} = \frac{2\sin\frac{k\pi t_c}{T}}{k\pi};$$

$$\omega_{ch} = k\omega_s;$$

$$\psi_{ch} = k\omega_s \frac{t_c}{2};$$

Substituting Eq. (3) into (1), we obtain the relation between the pulse signal at the output of the PE and the continuous signal at the input

$$A(t) = \frac{t_c}{T} x(t) + \frac{2t_c}{T} \sum_{n=1}^{\infty} \frac{\sin\frac{n\pi t_c}{T}}{\frac{n\pi t_c}{T}} x(t) \cdot \cos n\omega_s \left(t - \frac{t_c}{2}\right).$$

If a continuous input siganl, x(t), is a complex periodic function that can be presented as the sum, l, of the harmonic functions with frequencies in the band from 0 to f_0, then the frequency spectrum, x(t), is a line spectrum consisting of l lines. In this case, the line frequency spectrum of the pulse signal from the PE output will, in addition to the fundamental frequency spectrum for signal x(t), contain side frequencies differing from the fundamental frequencies by the magntiude $n\omega_s$ [3].

The side frequencies appearing as a result of the chopping can cause pulsations at the ARS output. A positioning link, connected to the PE output, is used to eliminate these undesirable pulsations, as well as to assist the manipulator slave in holding the position corresponding to the amplitude of signal A(t) for

time aT, where a ≤ 1. Each pulse from the PE is stored by the positioning link for time aT. In the majority of cases, the operation of the positioning link (PL), is based on a rapid accumulation of a charge by the capacitor during t_c, the time the control pulse is acting on the PL and subsequent retention of this charge for $t_c < t \leq aT$.

The PL thus converts the discrete signal from the PE output into a step-function signal (when a = 1), thereby approximating continuous input signal x(t). We have a zero-order PL when the indicated approximation occurs using current discrete values of the corresponding continuous signal.

Figure 3 is the block diagram of one manipulator drive. The following notations apply: k_1, k_2 are the "contacts" of the pulse element (switch); PL is the positioning link; W_s is the manipulator control system from the electronic amplifier to the piston of the working element. Figure 4 shows the time diagrams explaining the operation.

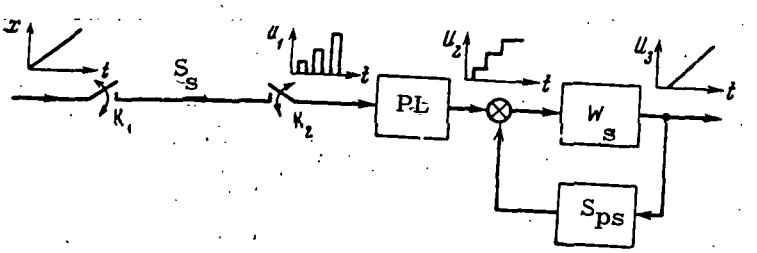

Figure 3. Block diagram of the discrete control of one manipulator drive.

The pulse transient function of a zero-order PL is a unit rectangular pulse of width aT [4]: Q(t) = 1(T) - 1(t - aT).

The PL transfer function will equal the Laplace transform of the pulse transient function [5]

$$K(p) = \int_0^\infty Q(t)\, e^{-pt} dt = \int_0^\infty 1e^{-pt} dt - \int_{aT}^\infty 1e^{-pt} dt = \frac{1}{p}(1 - e^{-paT}). \qquad (4)$$

The PL spectrum function, S_ω, can be obtained from the K(p) transform by replacing the operator p by jω, that is,

$$S_\omega = \frac{1 - e^{-j\omega aT}}{j\omega} = \frac{2\sin\frac{aT\omega}{2}}{\omega} e^{-j\omega aT/2}.$$

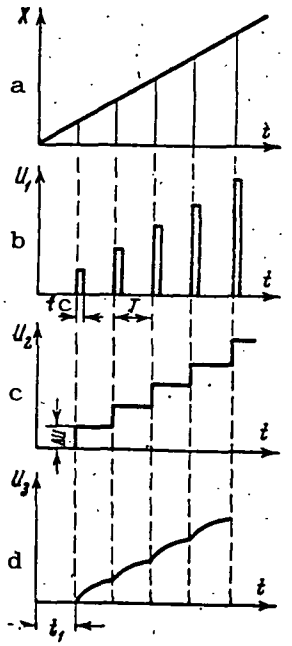

Figure 4. Time diagrams explaining the operation of the arrangement in Figure 3. a - x(t); b - $u_1(t)$; c - $u_2(t)$; d - $u_3(t)$.

The PL phase characteristic then will be $\Phi(\omega) = -aT \cdot \omega/2$.

What follows from consideration of the PL spectral function is that the introduction of the PL delays the signal at its output with respect to the input signal for a time equal to half the delay period aT. The amplitudes of the side frequencies different from the fundamental frequencies by $n\omega_s$ are reduced by the use of a PL. Eq. (4) shows that the positioning link functions as an integrator at high PE chopping frequencies.

The lower limit of the chopping frequency, ω_{smin}, thus can be determined from the Kotel'nikov theorem, from which it follows that if a continuous function, x(t), has a finite frequency spectrum from 0 to f_0 Hz, it can be completely determined (that is, the whole frequency spectrum, x(t), is transmitted) by the sequence of its discrete values following with period $T = 1/2f_0$ [6].

Thus, time T must be based on the condition that

(5)

to completely determine the continuous function x(t) with finite frequency spectrum 0 - 1 Hz, its discrete values after period T.

Period T should be selected as small as possible from the point of view of a reduction in the dealy caused by the PL and the bringing of its transfer function close to the integrator's function. On the other hand, the transient time, t_t, for the system, W_s, also imposes its requirements on T. When $T < t_t$ there is a transient dynamic error that will increase with time as x(t) changes (in Figure 4, the function x(t) is conditionally shown as changing linearly). /43

Time T is selected for the condition

$$t \geq t_t, \tag{6}$$

or for the condition $T > t_r$, where t_r is the transient rise time, depending on the nature of the transient (in the final analysis on system Q in terms of speed, K_Q).

It can be approximated that t_r is inversely dependent on system Q in terms of speed: $t_r = \pi/K_Q$.

Thus, increase in K_Q makes it possible to reduce delay time because of the reduction in T. In a real system, K_Q is selected on the basis of necessary operating speed, as well as to provide system invariance to disturbances caused by the load. Thus, the PE and PL parameters (in the final analysis, time T) are determined individually for each concrete system, depending on its K_Q.

Let us use Eq. (6) to find T for a real system with t_t = 360 msec

$$T \geqslant 360 \text{ msec}. \tag{7}$$

Thus, the PE in a real system must supply the PL input with discrete values of the continuous function x(t) with period

$$360 \text{msec} \leqslant T < 500 \text{ msec} \tag{8}$$

Taking T = 450 msec, we obtain

$$\omega_s = \frac{2\pi}{T} = \frac{2}{0{,}45} = 14 \text{ rad}$$

where n_0 is the number of commands transmitted over the communication channel.

Thus, the switch should switch channels with frequency $f_{ch} = 1/t_c$ = 36 Hz.

Figure 5 shows oscillograms of one slave drive with discrete control. The magnitude of the voltage of the "step" fed into the system input is 2.5 V.

The oscillogram shows that the time delay in the initiation of the movement of the working element, t_1, depends on the time of supply of the "step" relative to the time of supply of pulses from the PE output. The maximum t_1 can take is

$t_{lmax} = T$.

The oscillograms illustrate the possibility of the appearance of a transient dynamic error when the Eq. (7) condition is not satisfied. This is why K_Q was reduced in a real system (by reducing the amplifier gain and the capacity of the oil pump supplying the hydraulic system) which, in the finaly analysis, results in a $t_t > 360$ msec. Channel switching frequency simultaneously was increased to 83 Hz (t_c 12 msec, T = 168 msec). The oscillogram shows that the working element cannot "follow" the signal delivered in the form of a "step" in time T (the PE output pulse repetition period). The result will be an accumulation of the transient dynamic error when a "step" again is supplied in time T.

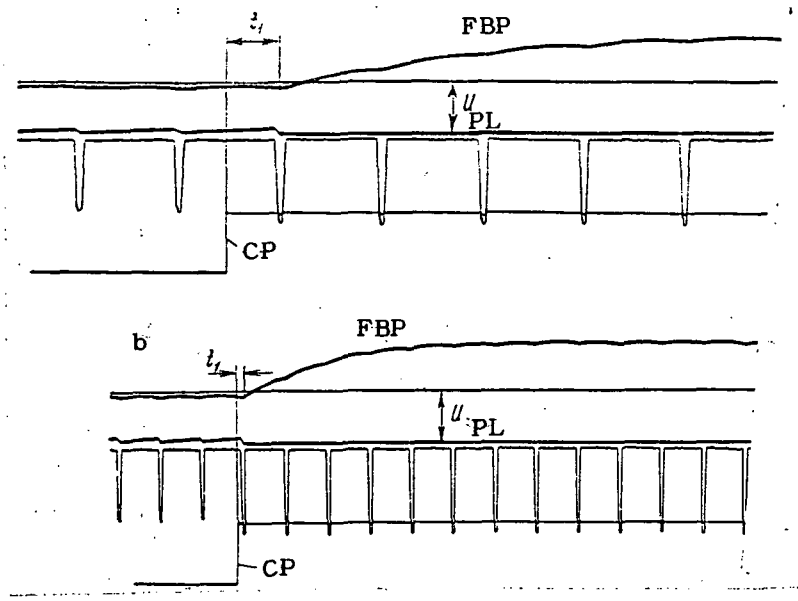

Figure 5. Oscillogram of the processes in a follow-up system with discrete control (the case of $T > t_t$). CP is the voltage across the cursor of the command potentiometer; U_{PL} is the voltage across the output of the positioning link; FBP - is the voltage across the cursor of the feedback potentiometer; a - when $I \geq 360$ msec; b - when $T \geq 360$ msec is not satisfied.

The following conclusion can be drawn from the foregoing.

1. Control of deep-water manipulators operating on the follow-up system principle with transmission of control signals over cables is possible only when a multiplex communication channel is used.

2. Most acceptable from the point of view of simplicity of design, dependability, and small size is time-division multiplexing.

3. The parameters of the pulse element for the time system for CC multiplexing are selected so as to provide the required manipulator dynamics for each concrete case.

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